Particle Energy And Acceleration Efficiencies In Highly Relativistic Shocks[1]

A.Meli and J.J.Quenby

Astrophysics Group, Blackett Laboratory Imperial College of Science,Technology and Medicine, London, UK

Abstract

In this paper we present an investigation of numerical Monte Carlo simulations of the diffusive shock acceleration in the test particle limit. Very high gamma flow astrophysical plasmas, have been used, from $\gamma_{up} \sim 50$ up to $\gamma_{up} \sim 1000$,which could be relevant to the suggested models of AGNs Jets and their Central Engines as well as the ultra-relativistic shock particle acceleration in Gamma Ray Burst (GRB) fireballs. Particularly the energy gain per shock crossing and the time constant for the above high relativistic processes is numerically calculated. We explicitly find a considerable γ^2 energy boosting in the first shock cycle, and in all subsequent shock cycles the particle energy is multiplied by a large factor. Also a noted acceleration speed-up for the same acceleration process has been observed. Both of those results are connected with theoretical suggestions that a significant enhancement of the acceleration process is possible due to relativistic effects not present at lower plasma flow speeds. The acceleration speed-up and the mean energy-gain per shock cycle found could efficiently justify the theory of the origin of Ultra High Energy Cosmic Rays (UHECR) from the sites of GRBs.

1 Introduction

Ultra-relativistic flow velocities are found in many astrophysical objects such as in Gamma Ray Bursts (GRB) as well as in AGN jets and their central engines where accretion is observed. The current understanding of multiwavelenght GRB afterglow observations, indicates that they are produced at the relativistic shocks, formed shortly after a violent explosion takes place where a blast wave impacts with the surrounding interstellar medium. Consequently shock waves form (Meszaros & Rees, 1993), and eventually relativistic diffusive shock acceleration takes place. Theoretical works of Vietri (1995,1997 and 1998) and Waxman (1995) suggested that diffusive

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acceleration at non-relativistic shocks is not fast enough to produce the highest energy particles observed, but they considered that a potential relativistic supesonic environment could succeed to do so. One of the first computational works (Quenby & Lieu, 1989)) concerning relativistic ($\gamma \sim$3) diffusive acceleration with application to AGN relativistic flows reported a considerable enhancement in the acceleration rate of a factor$\sim$13. In this present work we present a numerical investigation for diffusive acceleration in ultra-relativistic shocks with application to GRBs theoretical models.

The standard analytical theory of diffusive shock acceleration operating in one dimensional astrophysical non-relativistic flows, where u_1, u_2 are the non-relativistic upstream and downstream flow speeds and the particle's velocity is almost equal to c, yields a differential spectrum $dn/dp \propto p^{-\alpha}$, where $\alpha = r + 2/r + 1$ and $r = u_1/u_2$ and the analytically derived acceleration time constant is given by,

$$t_{acc} = \frac{c}{u_1 - u_2}[\frac{\lambda_1}{u_1} + \frac{\lambda_2}{u_2}] \tag{1}$$

where λ_1, λ_2 are the particle's mean free paths, upstream and downstream respectively. It is known that the fractional energy increase for a single shock crossing, for relativistic flows, is $\sim (1 - V^2/c^2)^{-0.5})$ where V is the relativistic difference $(u_1 - u_2)$ in flow velocities across the shock. Considering again relativistic flows and diffusion theory calculations for the cycle-time constant, it is found that the latter does not change from the non-relativistic case, and so we could expect a speed-up of acceleration, relative to the non-relativistic estimate. Because relativistic flows create large anisotropies in the plasma flow a detailed computational approach is necessary in this high γ regime. Several studies have been made by many authors, but still, there is a controversy about the rate of particles energy gain and the time constant of the acceleration. These controversies need a solution as they are crucial for models of AGN jet cosmic ray acceleration and UHECR production and acceleration in GRBs (eg Vietri). In this present work we present a Monte Carlo simulation, investigating the diffusive acceleration in ultra-relativistic parallel shocks for values up to $\gamma \sim 990$, with application to GRBs relativistic flows. We find a considerable acceleration rate enhancement and our results show explicitly that the energy boosting, scales as γ^2 in the first shock passaging cycle. After that, the particle energy is multiplied by a large number, gaining large amounts of energy which could still account for the theory of UHECR. These results support theoretical predictions (eg. Vietri 1995) concerning UHECR origin and acceleration from GRBs' highly relativistic plasma flows.

2 Numerical method

In this Monte Carlo code we consider both isotropic large angle and pitch angle diffusion which is calculated in the respective plasma rest frames, where particles are allowed to scatter in the respective fluid frames towards the shock. We consider only parallel shock ($\theta = 0$, where θ is the angle between the shock normal and the magnetic field), either because that is the field configuration, or turbulence removes "reflection" at the interface. A guiding centre approximation is used where the particle trajectory is followed in one-dimensional space along the x axis. A relativistic transformation is performed to the local plasma frames each time the particle scatters across the shock following it according to particle *jump conditions* and it is made leave the system from the moment that it 'escapes' far downstream at the spatial boundary or if it reaches a well defined maximum energy. The particles ($\sim 10^7$) of weight equal to one, are injected far upstream at a constant energy of high gamma, which supposes that a pre-acceleration of the particles has already taken place. They left to move towards the shock where along the way they collide with the pressumed scattering centers and consequently as they keep scattering between the upstream and downstream regions they gain each time an amount of energy. The compresion ratio is allowed to have the value of 4, for immediate comparison with the non-relativistic values. A main characteristic of the code is that a particle *splitting technique* is used, in order for the statistics to be as efficient as possible. The main notion of particle splitting is the fact that one can consider that each particle represents instead a large number of particles. When a number of particles escapes through the defined spatial or momentum boundaries during the acceleration process, we replace these *lost* particles with new ones -in order to have again the same initial number of particles- but in such a way that as their weight is decreased, the number of particles remains almost constant throughout the simulation. The probability that a particle will move a distance z along the field lines at pitch angle θ before it scatters is given by the following expression,

$$Prob(z) \sim exp(-z/\lambda|cos\theta|) \tag{2}$$

For the case of pitch angle diffusion scattering, the new pitch angle θ' is calculated by the trigonometric formula,

$$cos\theta' = cos\theta\sqrt{1 - sin^2\delta\theta} + sin\delta\theta\sqrt{1 - cos^2\theta}cos\phi \tag{3}$$

where $\phi\epsilon(0,2\pi)$ is the azimuth angle with respect to the original momentum direction. We note here that for the case of highly relativistic flows, the definition of particles pitch angle diffusion is scattering within an angle $\sim 1/\gamma_1$, where γ_1 is the upstream gamma measured in the shock frame (Gallant & Achterberg, 1999). This important condition is explicitly included in our Monte Carlo simulations during the relativistic particle shock acceleration process, having as a main aim to investigate and compare our results with controversial theoretical predictions which depend whether either large angle or pitch angle diffusion operates in highly relativistic flows.

3 Results

The aim of this work is to investigate the energy boosting of particles accelerated in higly relativistic shock waves in comparison to the shock cycle and to study the cycle time constant for the particle acceleration, by simulating highly relativistic shock formations which potentially occur in GRBs. The results shown in the figures, have been recorded in the downstream side, in the shock frame and concern large angle isotropic scattering and pitch angle diffusion for a various number of upstream Lorentz γ values. Figure 1, shows for both large angle scattering and pitch angle diffusion, the ratio of the computational time constant to the non-relativistic analytical acceleration time constant, as a function of the upstream Lorentz factor γ_{up} plasma flows. We note here that in the case of the pitch angle diffusion, we allow for the mean free path of particle to scatter $\sim \pi/2$ for the calculation of the analytical time-expression. We can observe that substantial 'speed-up' of a factor ~ 5 for large angle scattering is given and a considerable 'speed-up' of a factor ~ 200 is noted for pitch angle diffusion. The figures 2-5 show the mean energy gain of the accelerated particles versus the shock crossing where a substantial γ^2 boosting is found, explicitly for the first cycle. After that, and for the following shock crossings, the energy of the particle is multiplied by a large factor. Our first indication (γ^2) is in good aggreement with Gallant & Achterberg (1999) predictions who found *'that the energy of the particle for the first shock cycle is increased by a factor of γ_{up}^2'*. On the other hand though, they found that ...*'in all subsequent shock crossing cycles the particle energy doubles'* and that due to the fact that the particle does not have time to re-isotropise upstream before being overtaken by the shock. Our results show that the particle energy is multiplied by a large factor. This could be justified from the moment we could assume that the acceleration speed-up found, *gives* enough time for the particle to re-isotropise upstream before being overtaken by the shock.

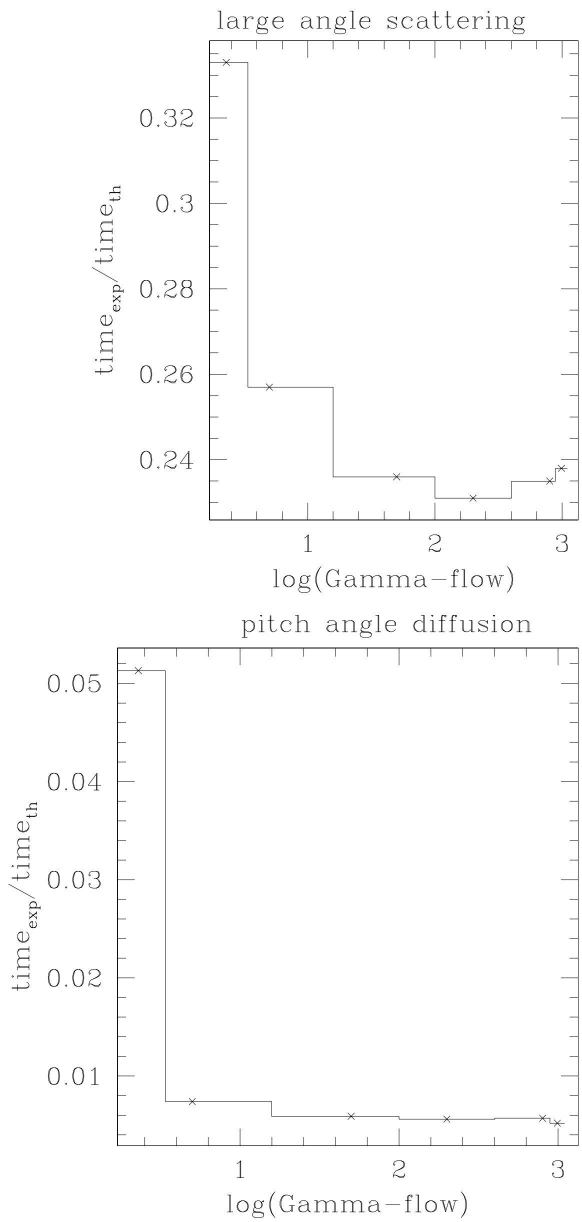


Figure 1: *Left*–The ratio of the computational to the non-relativistic analytical time constants for large angle scattering versus the Lorentz γ_{up} flow.*Right*–The equivalent plot for pitch angle diffusion. As it is seen, for both plots there is a maximum substantial 'speed up' of a factor ∼5 and ∼200, respectively.

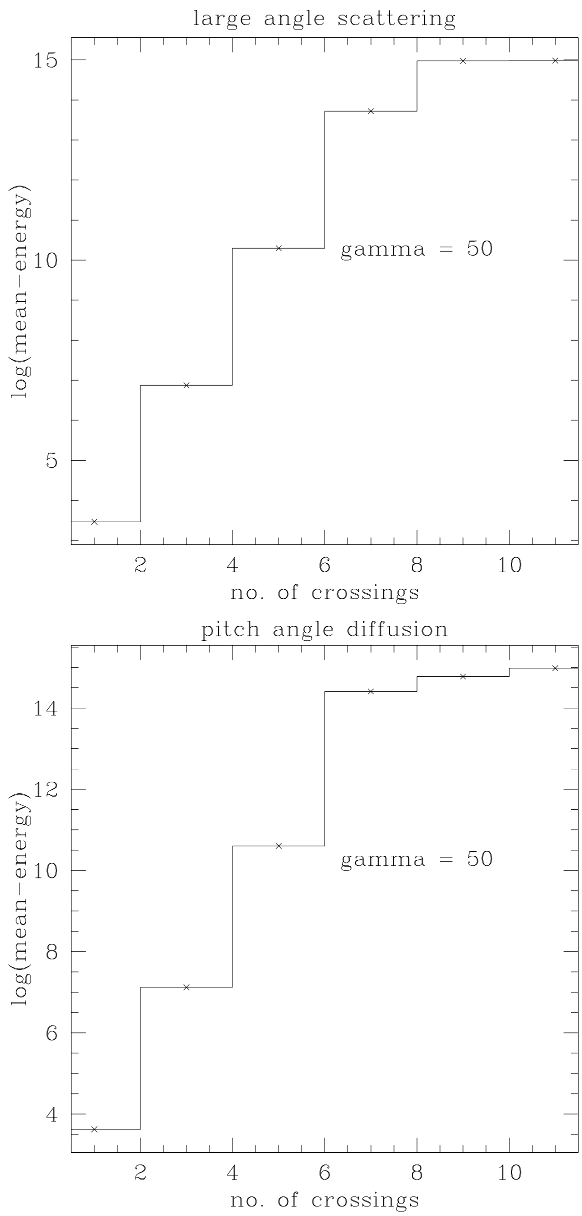
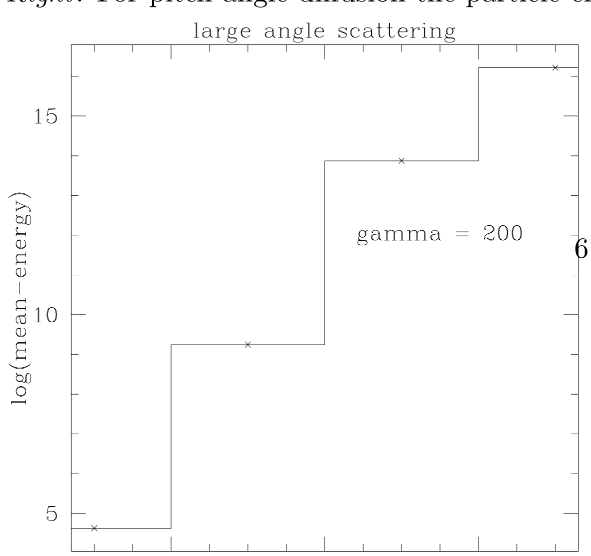


Figure 2: *Left*: For large angle scattering we calculate the mean energy of the particle versus the no. of shock crossings, employing an upstream flow gamma factor γ=50. We may observe the efficiency of the γ^2 boosting in the first cycle and the large energy multiplication in all subsequent crossings. *Right*: For pitch angle diffusion the particle energy gain appears (normally) to be less high.



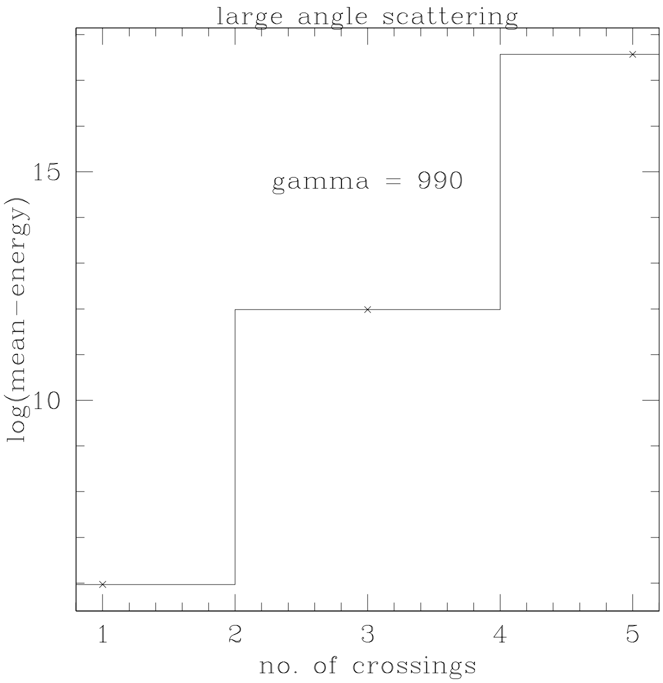


Figure 4: In this plot we use γ=990 for large angle diffusion. One may observe that the γ^2 energy boosting efficiency is explicitly present in the first shock cycle.

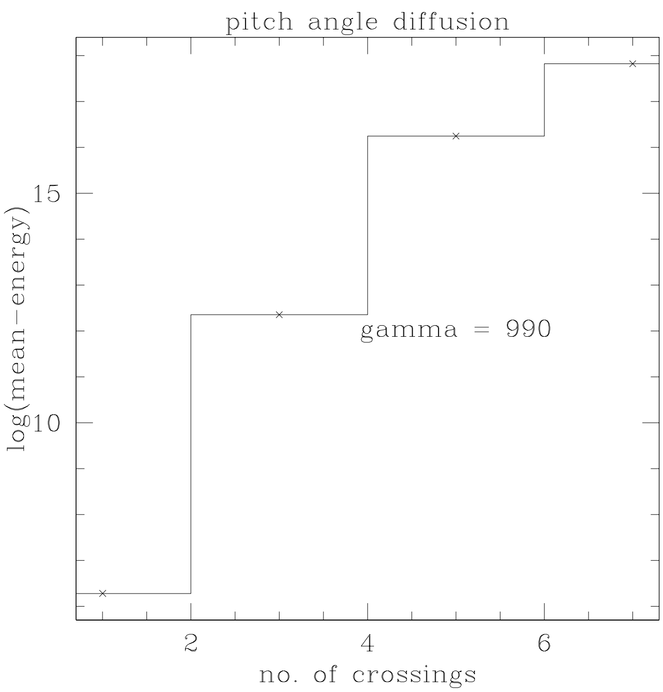


Figure 5: For pitch angle diffusion, the mean energy gain per cycle for γ=990, to be compared with the square of the upstream flow gamma factor γ^2 for the first shock cycle.

4 Conclusions

A Monte Carlo numerical investigation has been reported in the test particle limit of parallel diffusive shock acceleration. Very high gamma flow astrophysical plasmas have been used, from $\gamma_{up} \sim 50$ up to $\gamma_{up} \sim 1000$ which are relevant to highly relativistic astrophysical supersonic plasma flows in GRBs. A dramatic γ^2 energy boost in the first shock crossing cycle has been observed and a considerable acceleration speed-up has been found for both isotropic large angle and pitch angle diffusion. Both these results support Vietri and Waxman GRB models and theoretical predictions for the model of Ultra High Energy Cosmic Ray origin from GRBs. The surprising implication of those results is that a modeler could consider that, indeed there is a distinctive case showing that a γ^2 energy gain versus first shock crossing and a large energy multiplication in all other subsequent cycles is indeed happening in highly relativistic shock waves, 'making space' to the particles in order to gain rather very large amounts of energy in few shock cycles. On the other hand the above implications, along with our numerical calculations, finding a considerable acceleration speed-up could sufficiently account for the theoretical predictions implying UHECR origin from GRB relativistic shock configurations. However these crucial issues, need further detailed investigation as many other parameters need to be included within the simulation codes such as shock obliquity, non-linear processes and energy losses in order for potential models to be as realistic as possible with the actual relativistic flow of GRBs. There is already under way a similar work concerning the above parameters.

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5 ***References***

Baring, M.G, ICRC Salt Lake City, Proceedings (1999)
Bednarz, J. & Ostrowski, M. MNRAS 283, 447-456(1996)
Bednarz J. MNRAS 315L.37B(2000)
Bell, A.R., MNRAS 182,147-156(1978)
Bell, A.R , MNRAS 182,443-455(1978)
Blanfdord, R.D & Ostriker, J.P ApJ 211, 793-808(1977)
Ellison, D.C.,& Jones, F.C., & Reynolds,S.P., ApJ 360, 702 (1990a)
Gallant, Y.A., & Achterberg A., MNRAS 305L, 6G (1999)
Jones, F.C, Ellison, D.C Sp.Sc.R 58, 259-346(1991)
Kirk,J.G., & Schneider, P., ApJ 315, 425 (1987a)
Kirk, J.G, & Schneider, P. AJ 322, 256-265(1987)

Kirk,J.G., & Webb, G.M., ApJ 331 , 336 (1988)
Lieu, R., & Quenby, J.J., ApJ 350 , 692 (1990)
Meszaros,P., & Rees, M.J., ApJ 405, 278 (1993)
Ostrowski, M., MNRAS 249, 551-559(1991)
Ostrowski, M. & Schlickeiser R., Sol.Ph 167, 381-394(1996)
Peacock, J.A, MNRAS 196, 135-152(1981)
Quenby, J.J., & Lieu, R., Nature 342, 654(1989)
Quenby, J.J., Sp.Sc.R. 37, 201-237(1984)
Vietri, M., ApJ 453, 883(1995)
Vietri, M., Phys.Rev.Lett.78, 4328V(1997)
Vietri, M., ApJLet 488, L105(1998)
Waxman,E., Phys.Rev.Lett., 75, 386 (1995)